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DETAILED MAPPING OF THE WASHINGTON, HURRICANE, AND SEVIER/TOROWEAP FAULT ZONES, UTAH AND ARIZONA—USING NEW HIGH-RESOLUTION LIDAR DATA TO REDUCE EARTHQUAKE RISK

Collaborative research by the Utah Geological Survey and Arizona Geological Survey

Submitted by

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Utah fault mapping available through the UGS *Utah Geologic Hazards Portal* - https://geology.utah.gov/apps/hazards/

Arizona fault mapping available through the AZGS *Active Fault theme on the Natural Hazards in Arizona Viewer* - https://azgs.arizona.edu/quaternary-faults-natural-hazards-arizona-viewer

ABSTRACT

The Utah Geological Survey and the Arizona Geological Survey mapped Quaternary-active faults in southwestern Utah and northwestern Arizona using recently collected airborne high-resolution topographic lidar data. The late Cenozoic, west-dipping Washington, Hurricane, and Sevier/Toroweap fault zones define the seismically active transition zone between the Colorado Plateau and Basin and Range physiographic provinces in southwestern Utah and northwestern Arizona. These three fault zones pose a significant earthquake hazard to the St. George metropolitan area, which is the largest metropolitan area in Utah outside of the Wasatch Front and one of the fastest growing metropolitan areas in the U.S. We also took advantage of available lidar data and re-mapped additional faults adjacent to the Hurricane fault, including the Enoch graben, Parowan Valley, and Paragonah faults. Previously, the surface location and extent of fault traces associated with these fault zones were not well understood in many areas, owing to limited aerial photography coverage, heavy vegetation near range fronts, and the difficulty in recognizing moderate (<1 m) displacements in the field or on aerial photographs. Previous geologic mapping, paleoseismic investigations, historical aerial photography, and field investigations were also used to identify and map surface fault traces and infer fault locations. For faults that are mapped in Utah, special-study areas were delineated around faults to facilitate understanding of the surface-rupturing hazard and associated risk. Defining these special-study zones encourages the creation and implementation of municipal and county geologic-hazard ordinances dealing with hazardous faults in Utah. We identified 72 potential paleoseismic investigation sites where fault scarps appear relatively pristine, are located in geologically favorable settings, and where additional earthquake timing data would be beneficial to earthquake research of the faults mapped in this study. More accurate mapping and characterization of these faults help to mitigate earthquake risk in southwestern Utah and northwestern Arizona by creating surface-fault-rupture hazard maps (in Utah), refining fault segmentation models, and developing the paleoseismic fault parameters necessary for regional earthquake-hazard assessments.

INTRODUCTION

The Utah Geological Survey (UGS) and Arizona Geological Survey (AZGS) performed detailed fault-trace mapping for fault zones in southwestern Utah and northwestern Arizona (figure 1). Our investigation included: 1) mapping surface traces of southwestern Utah and northwestern Arizona faults at 1:10,000-scale using currently available high-resolution lidar data, aerial photography, and field reconnaissance; 2) identifying potential paleoseismic trenching sites for future investigation; 3) defining special study zones for fault traces in Utah for land-use planning, management, and local government ordinances and publishing in a feature-class layer in the UGS *Utah Geologic Hazards Portal*; 4) publishing new fault trace geometries and attributes to the UGS *Utah Geologic Hazards Portal*, the AZGS active fault theme on the *Natural Hazards in Arizona Viewer*, and shared with the U.S. Geological Survey (USGS) for updating the *Quaternary Fault and Fold Database of the United States;* and 5) presenting investigation results to professional groups, local governments, and the public in Utah and Arizona.

Southwestern Utah is experiencing rapid growth in urban and rural areas, specifically in the St. George-Hurricane and Cedar City metropolitan areas. The extent of scarps along the traces of the Washington fault zone (WFZ), Hurricane fault zone (HFZ), and the Sevier/Toroweap fault zone (STFZ) are not well understood in many areas owing to limited aerial photography for the area, difficulty in recognizing small to moderate (<1 m high) scarps in the field or on aerial photographs, and dense vegetation near range fronts in some areas. Accurately mapping and characterizing these active fault traces are essential to mitigating earthquake risk in southwestern Utah and northern Arizona, for updating the USGS National Seismic Hazard Maps, and for refining fault segmentation models and fault activity levels for use in regional earthquake-hazard assessments.

In Utah, the WFZ and HFZ trend directly through the rapidly urbanizing St.

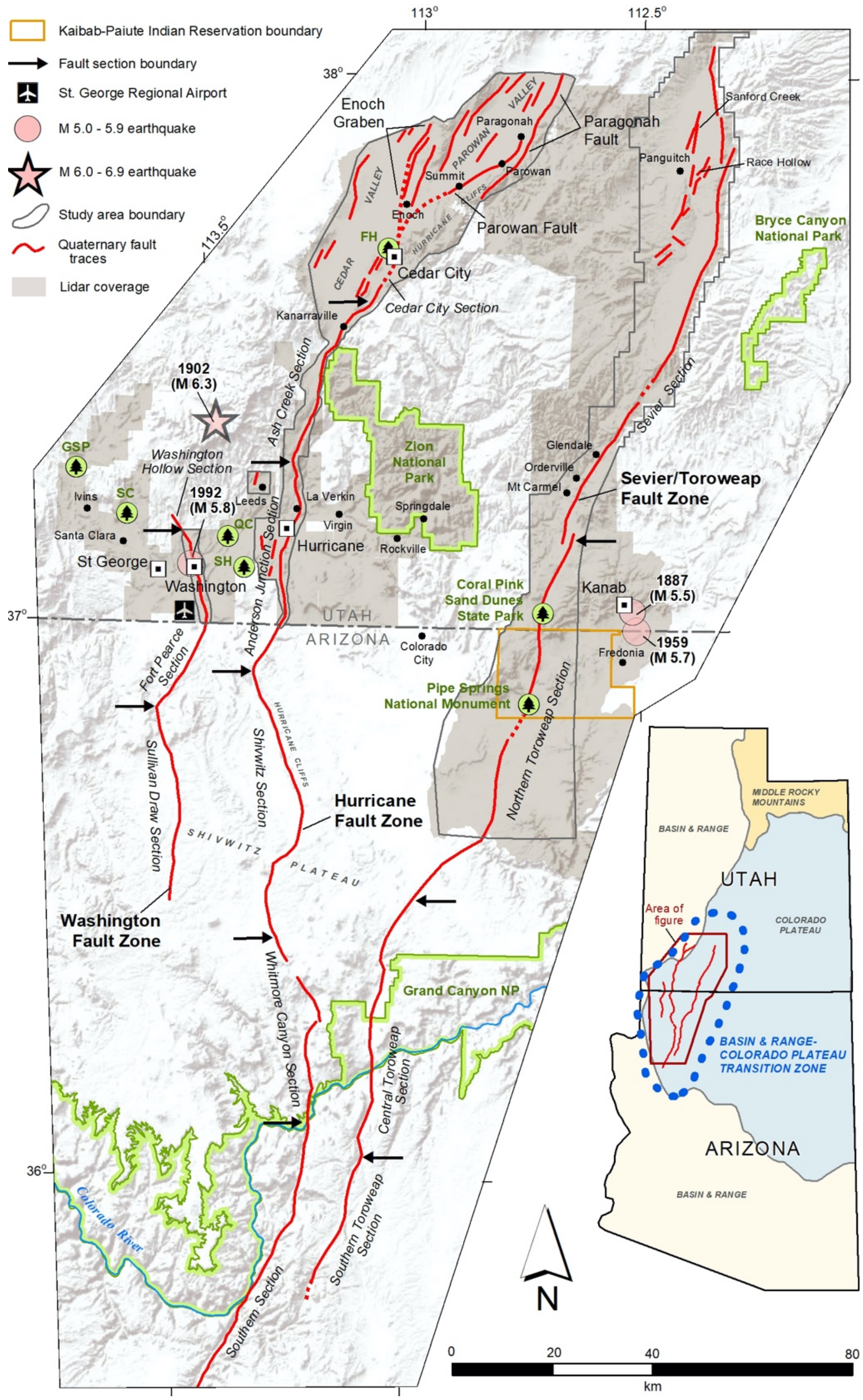

Figure 1. *Fault zones, cities, airborne lidar coverage, earthquake epicenters (University of Utah Seismograph Stations, 2019b), study-area boundary, and other physical and cultural features discussed. GSP=Gunlock State Park, SC=Snow Canyon State Park, QC=Quail Creek State Park, SH=Sand Hollow State Park, FH=Frontier Homestead State Park, M=earthquake magnitude. Inset shows study area in relation to the Basin and Range-Colorado Plateau transition zone. Shaded relief base map generated from ESRI, USGS, and NOAA elevation data.*

George metropolitan area—the largest population center in Utah outside of the Wasatch Front. From 2000 to 2006, the St. George metro area ranked as the fastest growing in the U.S. with a 39.8% growth rate (U.S. Census Bureau, 2007). Following the Great Recession of the late 2000s, the St. George metro area has ranked as the fifth fastest growing metro area in the U.S., seeing a population increase from 138,100 in 2010 to 171,700 in 2018 (U.S. Census Bureau, 2019). The State of Utah projects that the St. George region (Washington County) will continue to have the highest growth rate among Utah counties and that its population will exceed half a million (509,000) by 2065 (Perlich and others, 2017). The communities of Cedar City, Enoch, Kanarraville, and Parowan are adjacent to the HFZ (figure 1) and constitute most of the population in Iron County, which is projected to grow from 49,000 in 2015 to 90,000 by 2065 (Perlich and others, 2017). In addition, millions of tourists visit the region's popular national and state parks which would be directly impacted by a strong earthquake in the southwestern Utah-northwestern Arizona region. Potentially impacted parks include Zion, Grand Canyon, and Bryce Canyon National Parks, Pipe Springs National Monument, and Coral Pink Sand Dunes, Frontier Homestead, and Snow Canyon State Parks (figure 1). Strong ground-shaking would also result in numerous damaging earthquake-triggered rockfalls in many of these parks. Reservoir-based Sand Hollow, Gunlock, and Quail Creek State Parks are particularly vulnerable to large earthquakes because of their high-risk dams and dikes.

The WFZ, HFZ, and STFZ lie within the southern Intermountain Seismic Belt (ISB)—a north-south-trending zone of pronounced seismicity that extends from Montana to Las Vegas, Nevada (Smith and Sbar, 1974). Southwestern Utah and northwestern Arizona have a record of seismicity that includes the 1887 M 5.5 (estimated) Kanab, 1902 M 6.3 (estimated) Pine Valley, 1959 M 5.7 Fredonia, and 1992 M 5.8 St. George earthquakes (figure 1) that caused significant damage to nearby communities (e.g., Stover and Coffman, 1993; Christenson, 1995; University of Utah Seismograph Stations, 2019a, 2019b). Although a large surface-rupturing earthquake (> M 6.5) has not occurred historically in the region, scarps formed on soft bedrock units in Utah and alluvial-fan deposits in Arizona, and sparse paleoseismic investigations provide evidence that such large earthquakes have occurred in the late Quaternary.

For this UGS/AZGS/USGS-funded project, we have produced updated surface fault trace mapping of the WFZ, HFZ, and STFZ principally using high-resolution airborne lidar-derived imagery as well as aerial photographs, previous geologic mapping, and field investigations. Due to the proximity and possible structural associations with the HFZ, we also remapped the following faults that appear in the *Quaternary Fault and Fold Database of the United States*: Volcano Mountain faults, North Hills faults, Cross Hollow Hills faults, Cedar Valley (west and north side) faults, Enoch graben faults, Red Hills fault, Parowan Valley faults, Paragonah fault, part of the Markagunt Plateau faults, Sevier Valley faults north of Panguitch, and Sevier Valley (hills near Panguitch) faults and folds.

Our mapping shows surface fault geometries at 1:10,000 scale or greater; approximate age categories determined from previous paleoseismic investigations, geologic mapping, and geomorphic relationships; and, for faults within Utah, special-study zones (Lund and others, 2020). Age categories in the *Utah Geologic Hazards Portal* (https://geology.utah.gov/apps/hazards/) are based on Lund and others (2020) and Western States Seismic Policy Council (WSSPC, 2018) and will ensure a seamless integration of fault geometries and attributes into the USGS *Quaternary Fault and Fold Database of the United*

States. Additionally, these surface fault rupture hazard maps will be available through the UGS *Utah Geologic Hazards Portal* (https://geology.utah.gov/apps/hazards/). Surface fault rupture special-study zones can be implemented in geologic hazard ordinances (building setbacks, critical infrastructure avoidance, etc.) by local governments (Bowman, 2020) to reduce risk from surface faulting hazard. As part of this investigation, we identified potential paleoseismic trenching sites (table 1).

GEOLOGIC SETTING

Washington Fault

The west-dipping, north-trending Washington fault zone (WFZ) extends at least 100 km from north of St. George City southward across the Shivwitz Plateau of northern Arizona and was divided into the Fort Pearce and Washington Hollow sections in Utah by Knudsen (2015) (figure 1). Scarps formed on unconsolidated Quaternary deposits and soft bedrock, displaced late Quaternary lava flows, and limited paleoseismic data provide evidence for repeated late Quaternary surface faulting along the WFZ (e.g., Earth Sciences Associates, 1982, 1983; Menges and Pearthree, 1983; Peterson, 1983; Anderson and Christenson, 1989; Lund and Knudsen, 2015; Lund and others, 2015; Simon and others, 2015).

A USGS supported paleoseismic investigation of the Fort Pearce and Washington Hollow sections of the WFZ by the UGS (USGS award no. G11AP20061) (Lund, 2015) accomplished the following: (1) compiled and improved existing 1:24,000-scale mapping, (2) redefined the northern sections of the fault, (3) determined long-term slip rates from dated, fault-displaced lava flows, (4) completed a paleoseismic trenching investigation on the Fort Pearce section of the fault in Arizona, and (5) incorporated results from a consultant's surface-fault-rupture-hazard investigation completed on the fault near Washington City, Utah. Locating suitable trench sites on the WFZ in Utah has been difficult because fault scarps are commonly either formed on soft bedrock or are bedrock-cored, have been obscured by development (figure 2), or have not been recognized during aerial-photograph-based fault trace mapping. Due to these challenges, Lund and others (2015) decided to conduct a paleoseismic trenching investigation on an isolated scarp formed on a late Quaternary alluvial fan 6 km south of the Utah-Arizona state line. Their trenching investigation revealed evidence for two Holocene surface-faulting earthquakes and a tentative recurrence interval of 6600 years (Lund and others, 2015).

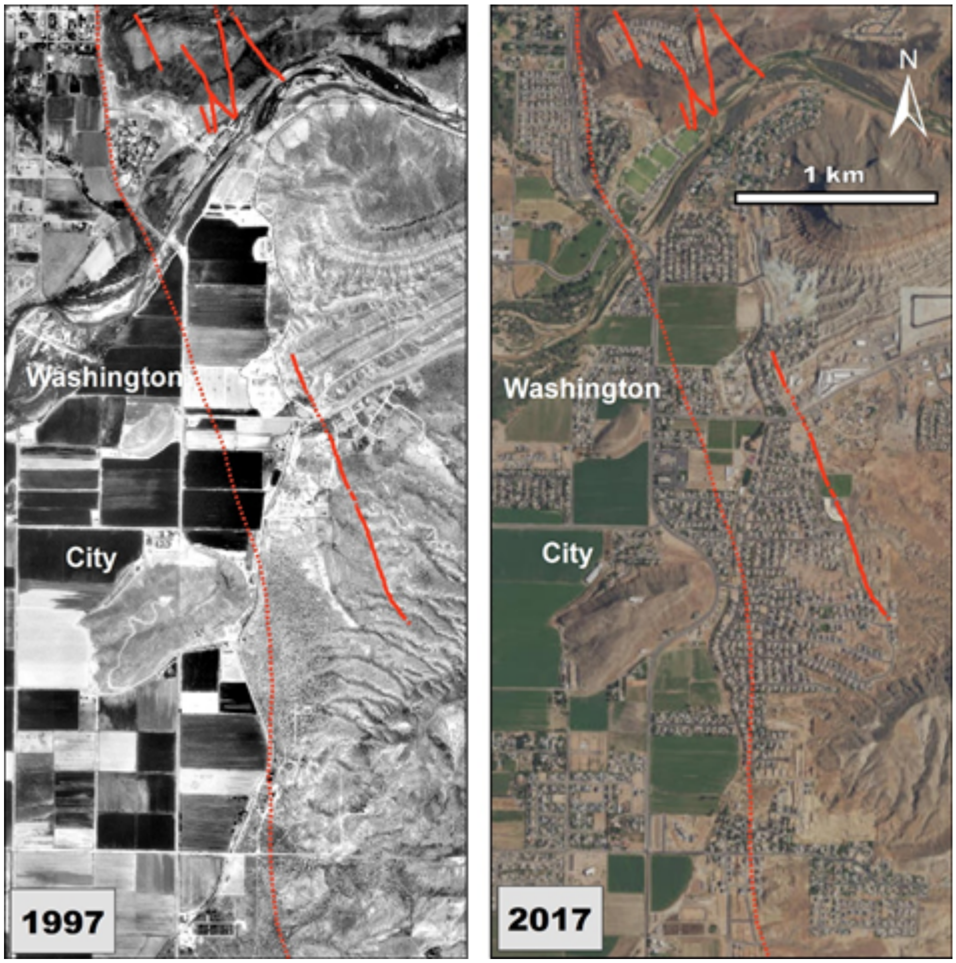

Figure 2 (left). *Comparison of aerial photography acquired in 1997 and 2017 showing rapid urban growth encroaching on the Washington fault zone in Washington City, Utah. Fault locations from Knudsen (2015); solid red line is a well-located fault, dotted red line is a concealed fault. 1997 image is U.S. Geological Survey digital orthophoto quadrangles (DOQs); 2017 image is Google Aerial Imagery.*

Hurricane Fault Zone

The Hurricane fault zone (HFZ) is one of the longest and most active of several large late Cenozoic, west-dipping normal faults within the structural transition between the Colorado Plateau and Basin and Range physiographic provinces. Hundreds to thousands of meters of vertical displacement on the HFZ have created a prominent escarpment, known as the Hurricane Cliffs, that extends more than 250 km from south of the Colorado River in Arizona northward to at least Cedar City, Utah (figure 1). Previous investigators have divided the HFZ into several smaller sections (figure 1) (e.g., Stewart and Taylor, 1996; Stenner and others, 1999; Lund and others, 2006). The Anderson Junction section trends directly through the towns of Hurricane and La Verkin in Utah and poses a significant fault surface-rupture hazard. In Iron County, the Cedar City section of the HFZ trends directly through Cedar City, posing a similar urban fault surface-rupture hazard. The UGS and AZGS cooperated on investigations of the HFZ in the late 1990s and early 2000s that were partially funded by USGS (award no. 1434-HQ-97-GR-03047) (Pearthree and others, 1998; Stenner and others, 1999; Lund and others, 2001; Amoroso and others, 2002; Lund and others, 2006). Stenner and others (1999) completed a paleoseismic trenching investigation on the HFZ 7 km south of the Utah-Arizona state line, where they found evidence for one Holocene surface-rupturing earthquake. Amoroso and others (2002) conducted a paleoseismic trenching investigation on the Shivwitz section of the fault in Arizona and found evidence for two late Pleistocene surface-rupturing earthquakes. In Utah, Lund and others (2006) targeted two potential trench sites on scarps between Kanarraville and Cedar City, but private-property access and abundant large boulders prevented them from exposing the fault zone. Lund and others (2006) instead focused on dating alluvial deposits overlying the fault zone and presented evidence for Holocene surface-faulting earthquakes along the Anderson Junction and Ash Creek sections and for late Pleistocene to Holocene activity on the Cedar City section.

Near Cedar City, the HFZ appears to bifurcate into north- and northeast-trending strands (figures 1 and 3). The north-trending strand extends beneath Cedar Valley and Enoch City before emerging as the western-bounding fault of the Enoch graben fault system (figure 1). The northeast-trending strand continues along the base of the Hurricane Cliffs and extends into Parowan Valley, where it is mapped as the Parowan and Paragonah faults (figures 1 and 2) (Anderson and Christenson, 1989; Maldonado and others, 1997; Biek and others, 2015). Although the Enoch graben and Paragonah faults have appeared on the Utah Quaternary Fault Parameters Working Group's (UQFPWG) fault-study priority list since its inception (Lund, 2005), no investigations beyond standard 1:24,000-scale geologic quadrangle mapping (Maldonado and Williams, 1993a; Maldonado and Moore, 1995; Knudsen, 2014a) have been completed for the fault zones. Likewise, additional faults that may be related to the HFZ, including the Parowan Valley faults, Red Hills fault, Markagunt Plateau faults, Cross Hollow Hills faults, North Hills faults, Cedar Valley faults, and Volcano Mountain faults (figure 3) are poorly understood and still await paleoseismic investigations.

Sevier/Toroweap Fault Zone

The west-dipping Sevier/Toroweap fault zone (STFZ) extends nearly 250 km from south of the Colorado River in Arizona to north of Panguitch, Utah (figure 1). Although a continuous structure, by convention, the fault is named the Toroweap fault in Arizona and the Sevier fault in Utah. The extent of fault traces along the STFZ in Utah and Arizona has been poorly defined due to a general lack of study, limitations of aerial-photograph-based mapping, and locally, difficulty in distinguishing fault scarps from landslide features.

A limited number of mostly reconnaissance-level paleoseismic investigations have been completed for parts of the STFZ. Geologic mapping and soils and geomorphic analyses by Jackson (1990) indicated Holocene surface rupture along the fault near the Grand Canyon. A data and map compilation of Arizona Quaternary faults by Pearthree (1998) divided the Toroweap fault into the southern, central, and northern Toroweap sections (figure 1). Anderson and Christenson (1989) examined scarps formed on Pleistocene alluvial-fan surfaces in the Sanford Creek and Race Hollow areas near Panguitch (figure 1). They gained access to a fault exposure along one of these scarps, in the wall of a commercial wood-chip disposal pit. They reported evidence of two surface faulting earthquakes; however, a lack of datable organic material in the fault exposure prevented determining precise earthquake timing at this site. Based on scarp morphologies, including topographic profiles and examination of a single trench, Anderson and Christenson (1989) estimated a middle to late Pleistocene age for most recent rupture on these faults. Paleoseismic reconnaissance of the STFZ by Lund and others (2008) indicated that the STFZ in Utah also likely consists of multiple sections. Lund and others (2008) could not locate scarps formed on unconsolidated deposits along the main trace of the STFZ in

Utah for paleoseismic trenching but used dated lava flows displaced by the fault to calculate vertical slip rates and recurrence intervals at two locations in Utah. Biek and others (2015) mapped much of the northern STFZ in Utah and suggested that a separate fault section may exist near Panguitch that would include the Sanford Creek and Race Hollow faults. Until detailed paleoseismic investigations are completed on the STFZ, individual paleoearthquake timing, displacement, and recurrence data will remain unavailable to inform accurate earthquake-hazard evaluations for this region.

DATA SOURCES

Lidar Elevation Data

Multiple sets of high-resolution USGS Quality Level 1 and 2 (QL1, QL2; Heidemann, 2018) lidar data were used to complete this project. All the data used was acquired by the State of Utah and its partners for fault mapping, urban planning, and other purposes. For the STFZ, 1-meter USGS QL1 data (Utah Geospatial Resource Center, 2016) collected around the Kanab, Utah, area were used for the southernmost extent of the mapping. For the remainder of the STFZ, 0.5- and 1-meter USGS QL1 & QL2 data (Utah Geospatial Resource Center, 2018) were used. We used QL1, high-resolution (1 m) lidar acquired in 2011 for mapping the HFZ and additional faults in Cedar Valley, Parowan Valley, and the western Markagunt Plateau (Utah Geospatial Resource Center, 2011). We used QL2, 1-meter lidar acquired in 2005 by the Natural Resources Conservation Service (U.S. Department of Agriculture, 2005) as the primary mapping tool for the WFZ. QL1, 1-meter lidar acquired in 2017 for much of Washington County (Utah Geospatial Resource Center, 2017) was also used as an additional resource for parts of the WFZ and southern HFZ. Lidar derivative products that were useful for identifying and refining surficial fault traces include slope-shade images, various hill shade images with different light illumination directions and altitudes, and contour lines. GlobalMapper (v.18) software was used to generate these images, as well as to generate topographic profiles perpendicular to scarps to investigate fault-scarp morphologies.

Aerial Photography

Historical aerial photography from the UGS Aerial Imagery Database (https://imagery.geology.utah.gov/) was used to map in urban areas where surface fault traces have been obscured by modern development, and to evaluate faults with possible historical movement due to groundwater depletion. Additionally, satellite imagery data (Utah Geospatial Reference Center, 2021) and National Agriculture Imagery Program (NAIP) digital aerial imagery was used to map fault traces, and was especially useful for mapping color changes along bedrock faults.

Previous Geologic Mapping

Large parts of the HFZ, WFZ, and STFZ are in the erosion-dominated Colorado River drainage basin. High rates of erosion have resulted in relatively sparse and/or thin alluvial deposits on or adjacent to the faults. Because large areas of bedrock are typically exposed near the faults on both the hanging wall and footwall, subsidiary bedrock faults that splay off the master fault are commonly exposed. Existing geologic maps were helpful as an aid to map subsidiary bedrock faults that are likely structurally linked to nearby master faults. Table 2 lists the geologic maps used to aid mapping for each fault zone.

FAULT MAPPING

Fault Interpretations

Washington Fault Zone

Much of the WFZ is expressed as prominent bedrock escarpments and the fault is rarely covered by unconsolidated deposits. Our lidar and aerial-photograph interpretations show a prominent 1- to 5-m-high scarp extends across much of downtown Washington City south of Interstate 15, although the fault is mostly concealed due to heavy urbanization. We identified a single scarp and potential trench site (site WF-02 in table 1) in this urbanized section that appears minimally disturbed. The scarp is likely largely formed on bedrock, but there may be sufficient unconsolidated material covering the fault to warrant a paleoseismic investigation. South of Washington City, a middle Pleistocene to Holocene mixed colluvial and alluvial deposit (unit Qcao of Hayden [2005]) is vertically offset about 3.5 m by the WFZ. The scarp is about 1.5 km south of the Washington Fields Exit of Utah State Route 7 (SR-7) and was discussed by Anderson and Chistenson (1989) and Knudsen (2015). This scarp is currently beyond the urbanized areas of Washington City and remains the best candidate for future paleoseismic trench investigations on the WFZ in Utah.

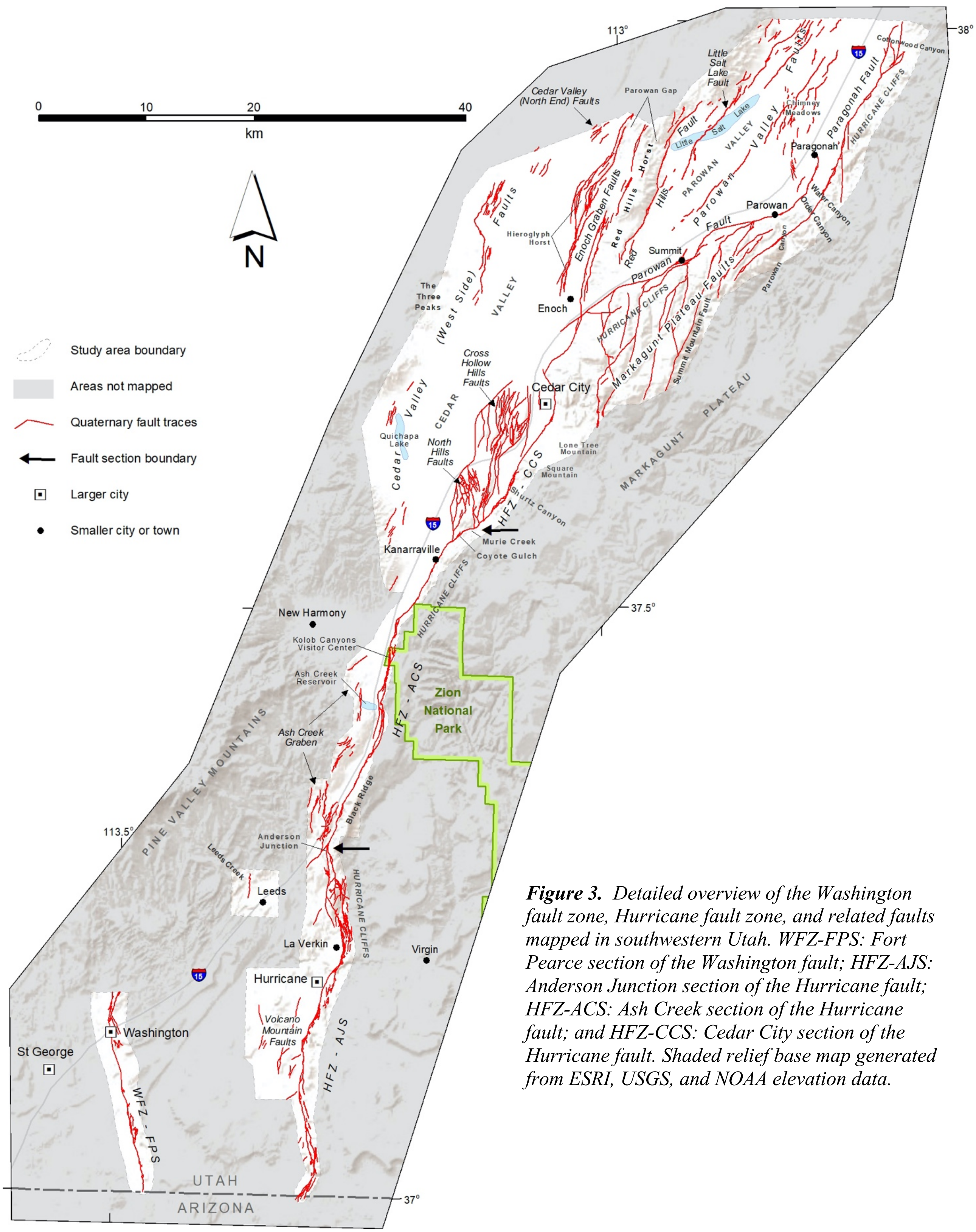

Figure 3. *Detailed overview of the Washington fault zone, Hurricane fault zone, and related faults mapped in southwestern Utah. WFZ-FPS: Fort Pearce section of the Washington fault; HFZ-AJS: Anderson Junction section of the Hurricane fault; HFZ-ACS: Ash Creek section of the Hurricane fault; and HFZ-CCS: Cedar City section of the Hurricane fault. Shaded relief base map generated from ESRI, USGS, and NOAA elevation data.*

Hurricane Fault Zone

Although the HFZ displaces Pleistocene basaltic lava flows 100s of meters, indicating a significant rate of Quaternary fault activity, only a few scarps have been found on potentially late Pleistocene- to Holocene-age unconsolidated deposits in Utah. We concur with Lund and others' (2006) paleoseismic investigation that subdivided the HFZ in Utah into three sections (from south to north): the Anderson Junction section, the Ash Creek section, and the Cedar City section (figure 1). Using our lidar-based mapping, we further evaluated scarps discussed by Lund and others (2006) and we hoped to find additional sites. Starting from south to north, we summarize our results below.

Anderson Junction Section

We mapped 35 km of the Anderson Junction section of the HFZ from the Arizona-Utah border northward to the Ash Creek section boundary at a prominent geometric bend near Anderson Junction (figure 3). The Anderson Junction section forms a steep, 300- to 400-m-high bedrock escarpment (Hurricane Cliffs) along most of its length. The fault typically juxtaposes resistant Paleozoic limestone and sandstone in the footwall against less resistant claystone, siltstone, and sandstone in the hanging wall that is partially mantled by colluvium. Many subsidiary faults splay off the main HFZ and are well exposed in the footwall. We used color aerial photography and existing detailed geologic mapping (table 1) to assist in mapping footwall faults that appear structurally linked to the master fault. Where exposed in natural stream cuts across the fault, youngest (middle to late Holocene) alluvium and colluvium near the mouths of large ephemeral drainages that extend across the fault are not displaced. About 7 km north of the Arizona-Utah border, we identified a single poorly preserved scarp formed on unconsolidated deposits. The moderately incised scarp is about 5 m high, 100 m long, and is formed on estimated Holocene-age alluvium (unit Qafy of Hayden [2004] and Biek and others [2009]). However, the scarp may be bedrock cored and is covered by abundant large boulders of talus and colluvium that would likely prohibit excavations.

Ash Creek Section

The Ash Creek section of the HFZ extends 33 km from Anderson Junction to Murie Creek northeast of Kanarraville (figure 3). The southernmost 15 km of the Ash Creek section resembles the Anderson Junction section and has formed a single high cliff (as much as 600 m high) of predominantly Paleozoic bedrock. North of Ash Creek Reservoir, the fault has produced a more subdued and complex scarp with multiple bevels where it forms the eastern margin of the New Harmony and Cedar Valley basins. Several prominent scarps are located along the base of the Black Ridge, but we agree with Lund and others (2006) that the scarps are simply bedrock scarps draped by a thin mantle of colluvium and are not amenable to trenching. A few stream-cut exposures reveal older (likely Pleistocene in age) colluvium in fault contact with bedrock, but overlying Holocene alluvium, where present, is unfaulted. Northward along the base of Black Ridge, Lund and others (2006) interpreted scarps formed on talus and shallow landslide deposits as most likely being related to slope failures. We found many of these scarps to be straight, rather than arcuate, indicating that they are likely products of surface rupture on through-going faults. However, their location in steep, rugged terrain makes them poor candidates for paleoseismic trenching investigations.

To the extent that lidar coverage allowed, we mapped a 15-km-long zone of mostly east-dipping fault scarps adjacent to and south of Ash Creek Reservoir that are antithetic to the Ash Creek section of the HFZ (figure 3). The scarps are 2 to 60 m high and formed on Pleistocene alluvial fans and the ~0.9 Ma (Biek and others, 2009) Pintura lava flow. This antithetic fault system, named the Ash Creek graben by Lund and others (2006), likely ruptures coseismically with the master HFZ, and therefore could be used as a proxy to understand the timing of large earthquakes on the Ash Creek section. Unlike scarps formed along the main strand of the HFZ at the base of the steep Hurricane Cliffs—where scarps are quickly destroyed or buried—Ash Creek graben scarps are well preserved since they are formed on gently sloping, largely inactive alluvial fans. We identified a couple of potential paleoseismic trenching sites on Ash Creek graben scarps that are formed on alluvial fans.

About 1 km south of Zion National Park's Kolob Canyons Visitor Center are a pair of short, poorly preserved scarps formed on mixed alluvium, colluvium, and talus (Lund and others' [2006] "Water Tank" site). The larger (~12 m high) eastern scarp is likely bedrock cored, but the western 4- to 5-m-high scarp appears amenable to trenching. A third fault strand is mapped farther east in footwall bedrock, which further complicates a potential paleoseismic investigation here. At the mouth of an unnamed drainage 3 km north of Kanarraville, the HFZ displaces the apex of a Holocene-active fan about 3 m ("Coyote Gulch" site of Lund and others [2006]). The fault there is uncomplicated and consists of a single strand. Although Lund and others (2006) were denied access to Coyote Gulch by the landowners, the site remains the best option for developing better timing information on the HFZ in Utah and we recommend renewed attempts to conduct a paleoseismic investigation there. Although Lund and others (2006) discussed additional scarps near Kanarraville, including a reported 5-m-high scarp at the mouth of an unnamed drainage 1 km north of Kanarraville (their "Kanarraville site"), we could not locate any scarps formed on alluvium for 15 km between the Water Tank and Coyote Hollow sites.

Cedar City Section

The Cedar City section of the HFZ as defined by Lund and others (2006) extends ~20 km from Murie Creek, near the southern end of the North Hills, to Cedar City (figure 3). The bedrock escarpment along the Cedar City section is formed on less-resistant Mesozoic siltstones and mudstones, resulting in markedly more cliff retreat and subdued slopes. About 2.5 km north of Murie Creek, four short (50–180 m long), closely spaced scarps are formed on pediment alluvium (unit Qap of Knudsen and others [in press]; "Bauer site" of Lund and others [2006]). The three eastern scarps are 2 to 5 m high and may be bedrock cored. The westernmost scarp is formed on the primary fault trace that appears to be buried by several meters of unfaulted late Pleistocene to Holocene alluvial-fan debris (unit Qaf_2 of Knudsen and others [in press]) sourced from a nearby unnamed drainage. A prominent 15- to 25-m-high scarp formed on pediment-mantled bedrock at the mouth of Shurtz Canyon has been mapped or mentioned in many studies (e.g., Averitt, 1962; Anderson and Christenson, 1989; Rowley and others, 2006; Lund and others, 2006). Lund and others (2006) attempted to trench the scarp, but they encountered problems due to the scarp's size and abundance of large boulders, and quickly abandoned their efforts. We found no viable potential trenching sites on the Shurtz Creek scarp, and we think the main fault is likely buried by several meters of unfaulted younger alluvial-fan deposits. About 1 km north of Shurtz Creek at the mouth of an unnamed drainage, closely spaced scarps are formed on pediment alluvium that mantles Mesozoic bedrock (Middleton site of Lund and others [2006]). We identified additional scarps that extend nearly 1 km farther south from what Lund and others (2006) mapped. Similar to what we found at the Bauer site, we conclude that many of the Middleton scarps may be bedrock cored and that the main fault trace is likely buried by several meters of unfaulted late Pleistocene to Holocene alluvium.

Southeast of Cedar City, large landslide complexes extend from their source areas on Lone Tree and Square Mountains to the valley floor. These landslides have buried the steep, step-like bedrock escarpment that characterizes the fault adjacent to Cedar City and farther south near Shurtz Creek. Conspicuous scarps as much as 20 m high are formed on the landslides that are aligned with the upward projection of where the HFZ is likely located. However, we suspect that displacement that created these scarps is largely differential settling of landslide material across the pre-existing, step-like fault escarpment. Although the possibility of some post-landslide tectonic surface rupture cannot be precluded, we have not included these scarps in our mapping.

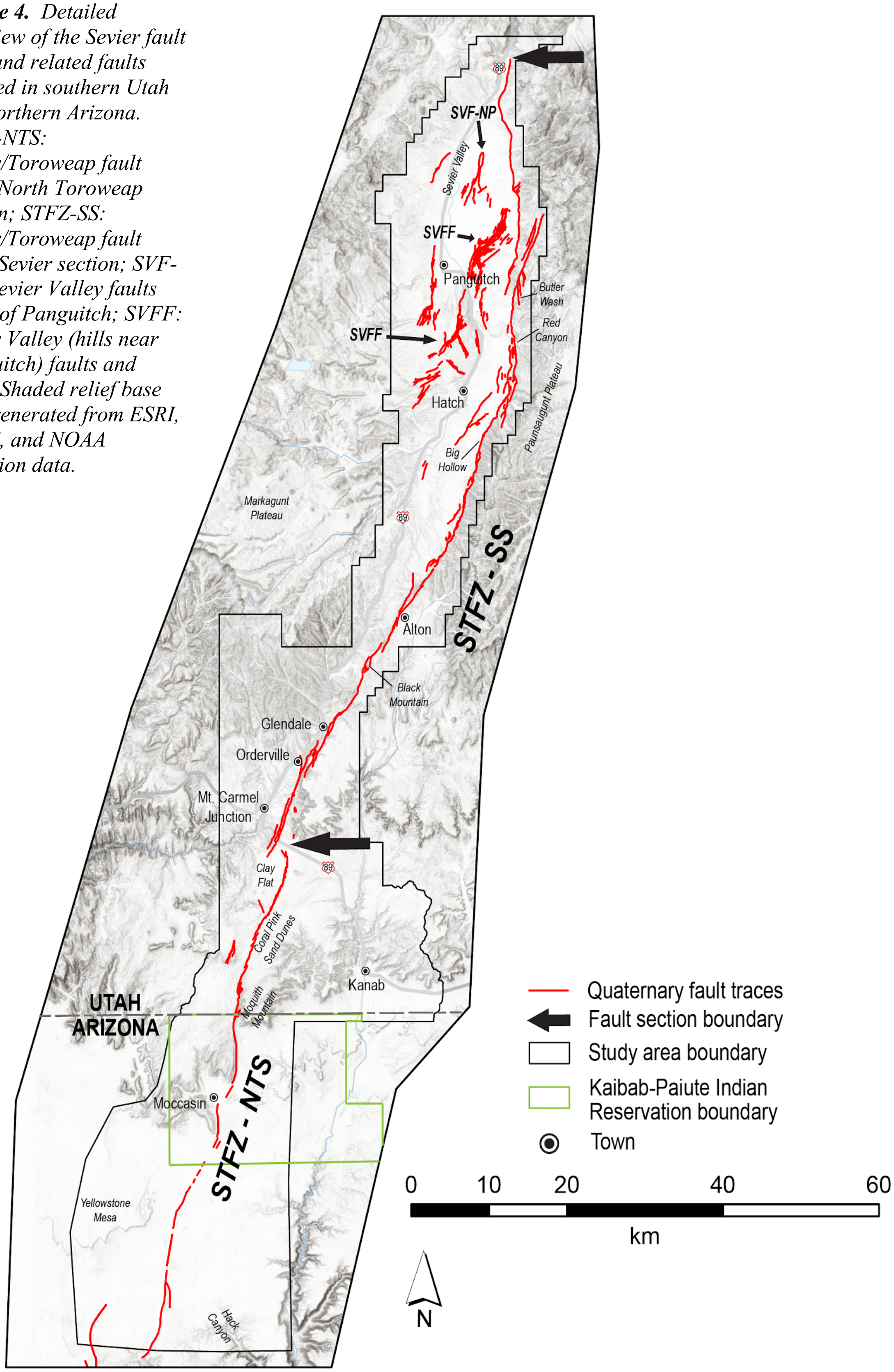

Figure 4. *Detailed overview of the Sevier fault zone and related faults mapped in southern Utah and northern Arizona. STFZ-NTS: Sevier/Toroweap fault zone, North Toroweap section; STFZ-SS: Sevier/Toroweap fault zone, Sevier section; SVF-NP: Sevier Valley faults north of Panguitch; SVFF: Sevier Valley (hills near Panguitch) faults and folds. Shaded relief base map generated from ESRI, USGS, and NOAA elevation data.*

Sevier/Toroweap Fault Zone

Northern Toroweap Section

The AZGS mapped approximately 45 km of the Northern Toroweap section of the STFZ from north of Hack Canyon on the Arizona Strip to the Arizona-Utah border (figure 4). The UGS mapped the remainder of the Northern Toroweap section from the Arizona-Utah border to the northern section boundary southwest of Mt. Carmel Junction, Utah, at approximately U.S. Highway 89.

In Arizona, several fault traces were found juxtaposing Paleozoic and Mesozoic bedrock with Quaternary landforms largely blanketed by eolian deposits. In the southern part of the mapping area, differential weathering between fine-grained claystones and mudstones, and sandstones and limestones of older bedrock formations (Permian Kaibab Formation, Triassic and Jurassic Formations) often appear linear and fault-like in nature. Previous mapping by Billingsley and others (2008) mapped traces that followed some of these differential erosional features; however, upon field examination in some limited areas, the fault appears to be concealed in structural valley bottoms or covered by alluvial-fan complexes. Near the low-lying central part of the mapping area, the evidence of faulting is either: (1) concealed by thin eolian deposits, (2) older than the oldest exposed deposits and alluvial landforms in this area, or (3) completely eroded away. A fault exposure along an arroyo complex juxtaposes older deposits and soils, perhaps late Quaternary, against Triassic sedimentary rocks. The fault zone's orientation in this central part of the mapping area is north-northeast. Several fault traces were delineated solely based on aerial images and lidar due to limited access on the Kaibab-Paiute Indian Reservation. Many fault strands appear to fault bedrock against younger landforms with eolian veneers.

Field reconnaissance for this study and by Menges and Pearthree (1983) resulted in identification of two potential paleoseismic sites in Arizona on the STFZ. Further examination is needed to confirm their potential in providing needed timing and displacement information for paleoearthquakes. Site 1 (table 1, STFZ-01) is located on the Kaibab-Paiute Indian Reservation, 0.6 km south of Arizona Highway 389. Menges and Pearthree visited the site in 1983 (Pearthree, personal communication, 2021). The fault zone at this site appears to offset a Quaternary alluvial fan as well as Triassic bedrock. Development of this site would require tribal permitting for additional reconnaissance and if suitable for excavation, an additional permit. Site 2 (table 1, STFZ-02) is located on Bureau of Land Management land just south of the reservation. A northeast-trending fault strand is exposed in an extensive arroyo system. A younger pebble gravel unit and two soils are faulted down against Triassic sedimentary rocks. The uppermost soil contains extensive whitish-buff bulbous soil structures that may be burrow fills. The uppermost soil exposed in the arroyo may be late Quaternary in age, but more detailed examination and sampling would be necessary to begin to assess the age of the youngest faulted soils.

The Northern Toroweap section from the Arizona-Utah boundary north mostly consists of bedrock fault scarps in the Jurassic Navajo Sandstone along the steep western flank of Moquith Mountain (figure 4). The fault trace is mostly buried where it crosses the eolian Coral

Pink Sand Dunes. However, a distinguishable lineament in the lidar data dissects the eolian deposits along trend with bedrock fault traces north and south of the dunes. We interpret this as eolian deposits draping over a bedrock fault scarp in the Navajo Sandstone. North of the sand dunes, the fault is again mostly expressed as a series of west-dipping bedrock scarps in Jurassic Navajo and Temple Cap Sandstones (Hayden, 2013).

The Clay Flat basin lies at the northern end of the Northern Toroweap section. This small, closed basin is formed by a left en-echelon step in the STFZ (Anderson and Christenson, 1989) and marks the segment boundary between the Northern Toroweap and Sevier sections of the fault zone (Lund and others, 2008). Anderson and Christenson (1989) suggested active late Pleistocene subsidence in this basin would be necessary to maintain a small, closed basin. Using the lidar data, we looked for any evidence of late Pleistocene faulting around the basin, but did not identify any. Undeformed basin-fill Holocene surficial deposits are perhaps masking any evidence of late Pleistocene faulting (Lund and others, 2008).

Sevier Section

The Sevier section of the STFZ runs approximately 88 km from Clay Flat to northeast of Panguitch (Lund and others, 2008). From Clay Flat northward to the town of Glendale, Utah, the fault is expressed as a series of right-stepping, overlapping bedrock scarps along the steep Navajo sandstone cliffs to the east. We identified several sharp, youthful-appearing scarps in the lidar data near the top of the Navajo cliffs just north of the town of Orderville, Utah (figure 4). However, although these scarps appear young in the lidar data, we attribute their sharp appearance to the fact that they were formed on durable sandstone and have resisted erosion.

Near Black Mountain (figure 4), the Sevier section offsets Quaternary volcanic rocks. These bedrock scarps have been well studied (Lund and others, 2008) and, along with offset volcanic rocks farther north at Red Canyon, they currently provide some of the only opportunities on the entire STFZ in Utah to provide long-term vertical slip rates and recurrence intervals. North and south of Black Mountain, the Sevier section is mapped as a buried bedrock fault. We expanded previous mapping of prominent bedrock scarps formed on volcanic rocks in the vicinity of Black Mountain.

Near the town of Alton, Utah (figure 4), a prominent 2- to 5-m-high west-dipping and uphill-facing fault scarp is present near the base of a much higher east-dipping obsequent fault-line scarp. An obsequent fault-line scarp forms where more-resistant rock in the hanging wall is in contact with less-resistant rock in the footwall, and erosion has inverted the topography. The large, east-facing obsequent fault-line scarp is formed on the stronger Tertiary Claron Formation rocks where it is juxtaposed against older, much weaker Cretaceous rocks, implying relatively low slip rates through much of the Quaternary (Lund and others, 2008). The smaller west-dipping scarp was interpreted by Anderson and Christenson (1989) as nonseismogenic, and they suggested the scarp may be the result of gravity-driven collapse of the mechanically weak Cretaceous Tropic Shale in the footwall of the fault. However, our new mapping shows this west-dipping, uphill-facing scarp to be much longer than previously thought. We mapped this approximately 15-km-long feature starting south of Alton and terminating near the western edge of the Paunsaugunt Plateau to the north. Due to its length and sharp appearance in the lidar data, we interpret this as being a seismogenic fault and part of the Sevier section of the STFZ. Several potential paleoseismic sites exist south of the town of Alton, but there is potentially shallow bedrock in the vicinity of all of them. One potential paleoseismic site exists just north of the town of Alton, on a small preserved part of a middle Pleistocene alluvial fan (table 1, STFZ-08). This may be one of the best sites for potential paleoseismic study on the entire STFZ in Utah, but more reconnaissance is needed to determine suitability for trenching.

North of Alton, the Sevier section is expressed as mostly bedrock scarps along the eastern edge of the Sevier Valley, marking the contact between Cretaceous and Tertiary rocks of the Paunsaugunt Plateau and the alluvial deposits of the valley. We identified one possible trench site near the mouth of Big Hollow Canyon on a small, preserved middle Pleistocene alluvial fan which appears to be cut by the fault. This site may present a good opportunity for paleoseismic data collection on a section of the fault which does not present many opportunities for trenching, but more reconnaissance is needed to determine the site's suitability for a paleoseismic study. As mentioned previously, the fault displaces Quaternary volcanic rocks in the vicinity of Red Canyon near Utah Highway 24 (figure 4; Lund and others, 2008), which currently provides average Quaternary vertical slip rates for the Sevier section. The northernmost several kilometers of the Sevier section mostly consist of a buried fault trace between alluvial deposits and bedrock along the flank of the Paunsaugunt Plateau. Near Butler Wash, we mapped several bedrock faults branching off the main trace into the bedrock based on prominent bedrock fault scarps visible in the lidar data. Despite an absence of faulted young deposits, these traces appear sharp in the lidar data, and along with highly visible plateau-margin morphology, suggest that they may be Quaternary active, and therefore worth mapping and creating special-study zones. Just south of Sanford Creek, several scarps exist on a small middle Pleistocene alluvial fan (table 1, STFZ-11 through STFZ-14), which may present a good opportunity for a paleoseismic investigation near the north terminus of the Sevier section of the STFZ.

The Sevier section terminates within the Miocene Marysvale volcanic field at the north end of the Sevier Valley. The STFZ continues to the north, through the Circleville and Marysvale Valleys, and into the Richfield metropolitan area, but mapping for these areas was not included as part of this project.

Additional Faults Mapped That Are in the *Quaternary Fault and Fold Database of the United States*

Enoch graben faults (#2528)

The Enoch graben faults are a series of generally north-northeast-trending, east- and west-dipping faults that extend north from Enoch. The faults collectively define the 18-km-long and 2-km-wide Enoch graben and adjacent 0.25- to 1-km-wide Hieroglyph horst to the west (figure 3). The west-dipping, range-bounding fault that defines the western margin of the Hieroglyph horst (called the West Red Hills fault by Maldonado and others [1997]) may be the northern extension of the HFZ as suggested by Maldonado and others (1994) and Biek and others (2015). Although we agree that this scenario is likely, for this study we leave it grouped with the Enoch graben faults. Faults on both sides of the Enoch graben have displaced late

Pleistocene to Holocene alluvial deposits and the ~1.3 Ma (Anderson and Mehnert, 1979; Best and others, 1980) Red Hills lava flow resulting in linear, well-developed scarps.

Many of the faults along the southwest margin of the Enoch graben have moved historically as much as 4 cm per year because of differential compaction of the valley aquifer caused by excessive groundwater pumping over the past century (Katzenstein, 2013; Knudsen and others, 2014). Ground subsidence and subsequent reactivation of pre-existing faults have made it difficult to discern whether youthful scarps formed on some Enoch graben faults are the product of Holocene rupture, historical fault creep, or a combination of both. For this study, we have only included tectonically produced fault scarps that we could identify on 1960, or older, aerial photographs—a time that likely predates significant subsidence due to groundwater withdrawals. A paleoseismic trenching investigation on such a fault would provide a rare opportunity to study a fault in a rapidly urbanizing area that has experienced both ~Holocene rupture and historical creep.

The northern half of the Enoch graben fault system is developed within the larger Red Hills horst block (figure 3) and is almost wholly contained within bedrock with sparse unconsolidated surficial deposits to help determine earthquake timing. However, we discovered a single pair of west-facing, 2-m-high scarps formed on a late Pleistocene to Holocene alluvial fan in central Parowan Gap that confirms a maximum age of late Pleistocene for most recent rupture for Enoch graben faults within the range block.

Cedar Valley (west side) faults (#2527)

Our mapping greatly expands the mostly east-dipping Quaternary fault system that defines the western margin of Cedar Valley. Prior to our investigation, fault scarps developed on unconsolidated deposits were not known south of The Three Peaks range. We discovered a group of short (<2 km) east- and west-dipping faults northwest of Quichapa Lake, and an additional group of similar fault scarps west of Kanarraville, that we assign to the Cedar Valley (west side) faults. Cedar Valley (west side) faults cut and displace late Pleistocene to Holocene alluvium (unit Qap of Knudsen [2014a], Knudsen and Biek [2014], and Knudsen and others [in press]) and therefore, we assign most of them to the late Quaternary (<130 ka) age category for most recent rupture. We identified four potential paleoseismic trench sites along the Cedar Valley (west side) faults (table 1).

Cedar Valley (north end) faults (#2529)

Available lidar data allowed us to remap more accurately a few of the southernmost fault scarps associated with the Cedar Valley (north end) faults. Recent geologic mapping by Knudsen and others (in press) shows that these faults displace late Pleistocene to Holocene alluvium (map units Qaf_2 and Qap), a similar relation observed for the Cedar Valley (west side) faults. Additionally, the morphologic surface expressions of the Cedar Valley (north end) faults appear similar to scarp morphologies of the late Quaternary (<130 ka) Cedar Valley (west side) faults. For these reasons, we assign the Cedar Valley (north end) to the late Quaternary (<130 ka) age category for most recent rupture.

North Hills faults (#2522)

We greatly expanded the density and extent of mapped Quaternary faults exposed in the North Hills horst block north of Kanarraville (figure 3). Several faults have cut and displaced the ~1.1 Ma (Anderson and Mehnert, 1979) North Hills lava flow and late Tertiary to early Quaternary basin-fill alluvium (unit QTaf of Biek and Hayden [2016] and Knudsen and others [in press]). We found no scarps formed on late Pleistocene to Holocene alluvium that overlies parts of the North Hills faults. The morphology of moderately dissected scarps formed on QTaf is consistent with Anderson and Christenson's (1989) middle Pleistocene or younger (<750 ka) age estimate for most recent rupture on the North Hills faults.

Cross Hollow Hills faults (#2524)

We greatly expanded the density and extent of Quaternary faults exposed in the Cross Hollow Hills horst block near Cedar City. On the eastern side of the Cross Hollows Hills horst, faults have cut and vertically displaced the ~1.1 Ma (Knudsen, 2014b) Cross Hollow Hills lava flow several meters. Relatively straight, youthful-appearing scarps formed on late Tertiary to early Quaternary basin-fill alluvium (unit QTaf) are indicative of middle Pleistocene surface faulting. Late Pleistocene to Holocene alluvium is unbroken by underlying faults. The Cross Hollow Hills faults were previously assigned to the Quaternary (<2.6 Ma) age category by Anderson and Christenson (1989) because they lacked age information for the displaced lava flow that we now know is 1.1 million years old. Since we found the Cross Hollow Hills faults to be strikingly similar, in terms of displaced units and general scarp morphology, to the nearby North Hills faults, we recommend a middle Pleistocene or younger age designation (<750 ka) for the Cross Hollow Hills faults.

Red Hills Fault (#2532)

The Red Hills fault defines the boundary of the Parowan Valley graben to the east and the Red Hills horst to the west. As described by Anderson and Christenson (1989), the Red Hills fault exhibits a morphologically youthful appearance with steep, straight bedrock scarps and faceted spurs. For about 7 km south of Parowan Gap, the Red Hills fault places Tertiary and Cretaceous bedrock in fault contact with both middle to late Pleistocene alluvial-fan deposits (unit Qafo of Biek and others [2015]) and late Pleistocene to Holocene alluvial-fan deposits (unit Qafy of Biek and others [2015]). At the southern end of the fault, near Braffits Creek, east- and west-dipping strands of the Red Hills fault cut and vertically displace the ~1 Ma (Anderson and Mehnert, 1979) Summit lava flow. We traced one east-dipping strand that cuts the Summit lava flow northward where the strand has produced a low (<1 m high), poorly preserved scarp in late Pleistocene to Holocene alluvium (unit Qafc of Biek and others [2015]). Farther north, northwest of the Little Salt Lake, the morphological expression of the Red Hills fault becomes more subdued, and scarps formed on alluvium are highly eroded and discontinuous, indicative of lower activity rates throughout the late Quaternary.

Parowan Valley faults (#2533)

The Parowan Valley faults have produced a widespread, and locally dense, zone of intrabasin fault scarps throughout much of Parowan Valley (figure 3). Faults on the east side of the valley generally dip west and faults on the west side of the valley generally dip east. Many of the scarps are less than 1 to 2 m high and are likely the result of a single surface-faulting earthquake. Our lidar analysis revealed many previously unmapped scarps that are not apparent on aerial photography due to their small (<1 m) scarp height. In terms of continuity, length, and scarp height (as much as 12 m), the Little Salt Lake fault (Maldonado and Williams, 1993a; Williams and Maldonado, 1995) is the most prominent Parowan Valley fault. We traced the Little Salt Lake fault scarp an additional 7 km to the south compared to the previous mapping of Maldonado and Williams (1993a, 1993b). The newly recognized southward extension of the Little Salt Lake fault has displaced the Little Salt Lake playa surface, indicating probable late Holocene rupture. Similar to the Enoch graben area, excessive groundwater pumping and related ground subsidence are affecting parts of Parowan Valley (DuRoss and Kirby, 2004; Smith and Li, 2021) and we suspect subsidence may be causing some amount of creep on part of the Little Salt Lake fault.

In the central part of the valley, near Chimney Meadows (figure 3), the Little Salt Lake fault has formed scarps across Holocene-active stream channels and terraces (unit Qaly of Biek and others [2015]) and the scarps may represent the youngest surface ruptures known in southwestern Utah (Anderson and Chistenson, 1989; this study).

Paragonah fault (#2534)

The Paragonah fault defines the northeast margin of Parowan Valley and resembles the Red Hills fault with generally youthful morphologic features including straight and steep bedrock scarps, faceted spurs, and lack of embayed footwall drainages. South of Paragonah, the fault displaces the ~0.4 Ma (Fleck and others, 1975) Water Canyon lava flow, although part of the apparent displacement may be due to the lava cascading over a pre-existing scarp.

The main trace of the Paragonah fault is commonly at the bedrock-alluvium contact, where recent rupture is either not apparent, or the fault is buried by unfaulted late Holocene colluvium and alluvium. At the northernmost mapped extent near Cottonwood Canyon (figure 3), less pronounced late Quaternary activity on the Paragonah fault has resulted in considerable cliff retreat and deposition of alluvial fans across the fault. A few deeply incised and discontinuous 4- to 5-m-high scarps near Cottonwood Canyon have formed on middle to late Pleistocene alluvial-fan deposits (map unit Qafo of Biek and others [2015]). Holocene-age alluvial units that partially bury Paragonah fault strands near Cottonwood Canyon are not displaced.

In addition to the scarps formed on older alluvium at the north end of the fault, we identified a single 0.5-km-long scarp formed on a late Pleistocene to Holocene alluvial fan (map unit Qafy of Biek and others [2015]) southeast of Paragonah. However, the scarp is in a structurally complex area and is formed on one of three fault strands that compose the fault zone at this latitude.

Near Paragonah, an additional west-dipping fault 1 km west of, and parallel to the Paragonah fault appears in an en echelon right-step relation (figure 3). Southward, near Parowan, the western companion fault bends to the west-southwest and defines the valley margin and range front, whereas the Paragonah fault continues to the south-southwest and enters the Markagunt Plateau block (figure 3). We follow the mapping of Biek and others (2015) and refer to the range-bounding fault near Parowan as the Parowan fault (described below).

Markagunt Plateau faults (#2535)

The Markagunt Plateau faults comprise a wide zone of east- and west-dipping faults that have broken and extended the northwestern quadrant of the Markagunt Plateau (figure 3). Available lidar data allowed us to remap a few of the westernmost faults in this system. Being wholly contained within the elevated and erosion-dominated Markagunt Plateau block, sparse alluvial deposits overlapping the faults could help evaluate their most recent activity. However, we identified a single 2-m-high, east-facing scarp formed on late Pleistocene to Holocene alluvium and colluvium (unit Qca of Biek and others [2015]) near the northern end of the Summit Mountain fault (figure 3) of Biek and others (2015). The scarp is 200 m long and deeply dissected. Despite a lack of scarps on alluvium, the morphology of bedrock scarps on the Markagunt Plateau faults is consistent with Anderson and Christenson's (1989) estimated middle Quaternary age for most recent surface faulting.

The tectonic origin of Markagunt Plateau fault scarps has been questioned due to abundant landslides that partially mask some parts of the faults. Anderson and Christenson (1989) suggested that some scarps could be the result of gravitational spreading and therefore may not be tectonically produced. This uncertainty led Black and Hecker (1999a) to designate the Markagunt Plateau faults as Class B structures. However, with the aid of lidar imagery, we could clearly distinguish landslide features from tectonic fault scarps, and we are confident that our mapped faults are through-going structures of tectonic origin—a similar conclusion reached by Biek and others (2015). We therefore recommend changing the Markagunt Plateau faults from the Class B to the Class A category.

Volcano Mountain faults (#2520)

The Volcano Mountain faults are a zone of generally north-northeast-trending, east- and west-dipping faults south of Volcano Mountain near Hurricane. The faults displace the ~1 Ma Ivans Knoll, Ramparts, and Grass Valley lava flows (Biek, 2003a; Hayden, 2004; Biek and others, 2009). We found no scarps formed on unconsolidated deposits. Earlier studies showed the Volcano Mountain faults displacing the 0.35 Ma Volcano Mountain lava flow (Sanchez; 1995; Biek, 1998), which led Black and Hecker (1999b) to designate a middle Quaternary (<750 ka) age for latest surface rupture. However, more recent, detailed mapping of the lava flows (Biek, 2003a; Hayden, 2004; Biek and others, 2009; this study) revealed that the Volcano Mountain flow is uncut by the Volcano Mountain faults. We therefore consider the age of most recent movement on the Volcano Mountain faults to be Quaternary or younger (<2.6 Ma).

Sevier Valley faults north of Panguitch (#2536)

We expanded and remapped several horst and graben block structures due north of Panguitch in the middle of Sevier Valley (figure 4). Lund and others (2008) refer to the primary horst block here as the Sanford Creek horst. These faults lie approximately 5 km west of the main trace of the Sevier section of the STFZ. Our new mapping greatly expands the extent and detail level of scarps in this area. Several large (10+ m) scarps exist on late to middle Pleistocene-age alluvial fans east of the Sevier River. We extended these scarps to the south, where they decrease in height, ranging from 0.5 to 1 m. We identified several potential paleoseismic sites along these horst and graben structures for future study. Combining several of these sites with the site identified on the Sevier section of the STFZ just south of Sanford Creek (table 1, sites STFZ-11 through STFZ-14) would provide information on the relationship between these two fault systems.

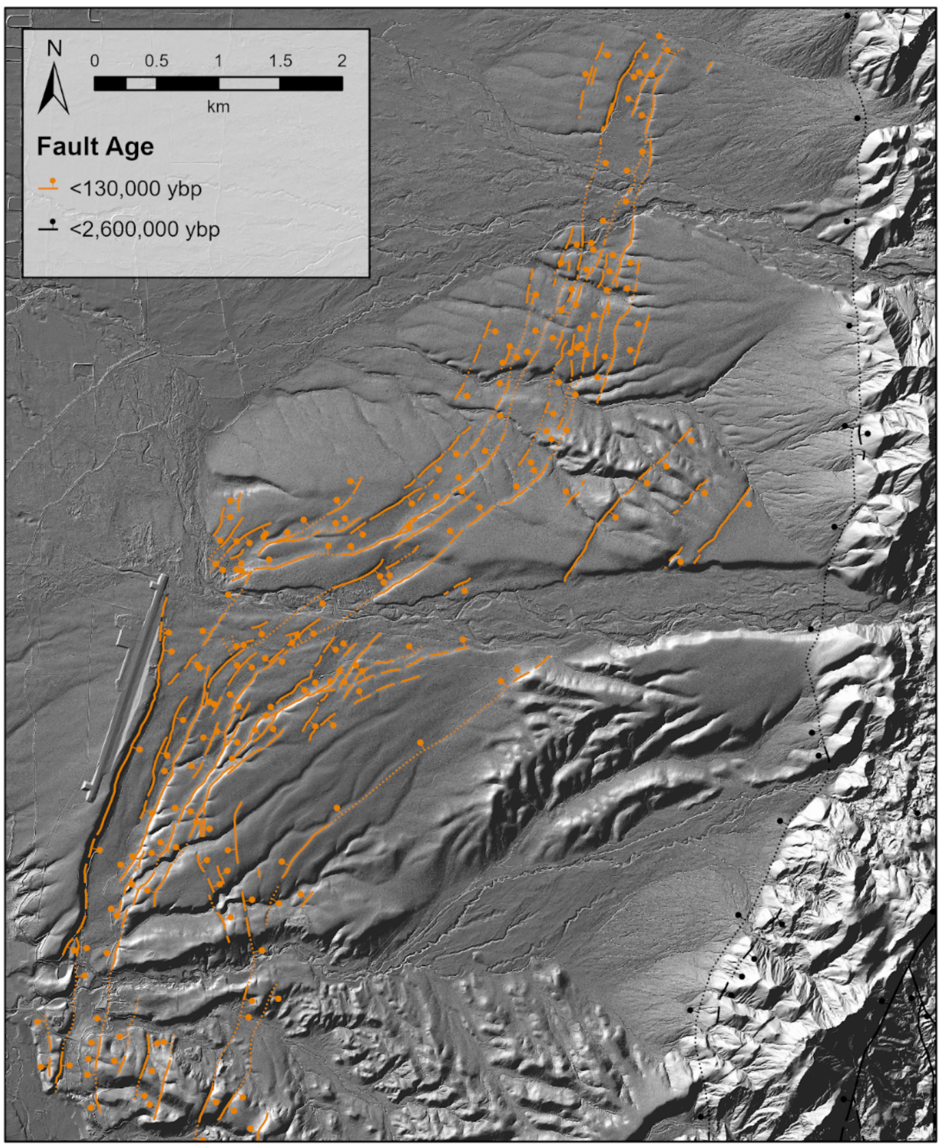

Figure 5 (left). *Lidar-derived hillshade image showing Sevier Valley (Hills near Panguitch) faults and folds. Fault mapping confidence shown as solid line where "well constrained," dashed line where "moderately constrained," and dotted line where "inferred."*

Sevier Valley (Hills near Panguitch) faults and folds (#2537)

Our new mapping greatly expands the density and extent of the Sevier Valley (Hills near Panguitch) faults and folds (figure 4). These faults had been mapped previously by Biek and others (2015), but the extent and detail level of mapping has been greatly expanded. This zone lies approximately 5 to 8 km to the east of the main trace of the Sevier section of the STFZ. The diffuse zone consists of broad anticlines and synclines, the largest of which is called the Race Hollow syncline, near the Panguitch airport. Extensive fold-parallel fault scarps form numerous small and large grabens (figure 5). East and northeast of Panguitch, scarps are mostly formed on late to middle Pleistocene alluvial-fan deposits. To the southwest, where the fold axis crosses the Sevier River, fault scarps cut older late Quaternary and Tertiary deposits. We interpret these scarps as all being part of the same system. However, the origin of faulting and relationship to the main trace of the STFZ is unknown. Further study is needed to determine if this zone is seismogenic, or perhaps related to volcanism or local uplift. We identified several potential paleoseismic trenching sites throughout this area; however, many additional sites exist due to the broad, extensive zone of faulting and lack of development. A paleoseismic study for this zone would require trenching multiple scarps across the zone to capture the entire paleoearthquake record. Additional trenches on the main trace of the STFZ would be necessary to determine the relationship between the two zones. Even though they are not part of the Sevier section of the STFZ, these present perhaps the best available trenching opportunities anywhere along the entire fault zone.

Additional Faults Mapped That Are Not in the *Quaternary Fault and Fold Database of the United States*

Parowan fault (#2558 [new number])

Although a major basin-bounding fault has been recognized along the southeast margin of Parowan Valley (e.g., Maldonado and Moore, 1995; Maldonado and others, 1997; Hurlow, 2002; Biek and others, 2015), no fault appears here in the *Quaternary Fault and Fold Database of the United States*. Biek and others (2015) named the fault and showed that it displaces late Pleistocene to Holocene alluvial-fan deposits (units Qaf_2 and Qafc of Biek and others [2015]). We follow Biek and others (2015) and use the name Parowan fault. In addition to several scarps that Biek and others (2015) mapped northeast of Summit and at the mouth of Parowan Canyon, we identified additional scarps on unconsolidated deposits near the mouth of Order Canyon south-southwest of Paragonah.

Faults near Leeds

A previously unrecognized north-trending fault near Leeds has produced a prominent east-facing scarp as much as 10 m high. The fault displaces the Pleistocene, largely inactive alluvial fan (unit Qafo of Biek and others, 2009) that issues from Leeds Creek Canyon. The fault traverses an area undergoing significant residential development and becomes difficult to map to the north where it enters a large expanse of Navajo Sandstone. The fault likely continues farther south beneath an area disturbed by mining activities and may be partially responsible for the down-to-the-east displacement of the Buckeye Reef (prominent hogsback of Jurassic Springdale Sandstone Member of the Kayenta Formation) north of Interstate 15.

Fault Traces

Fault traces were mapped according to standards and experience of the UGS and AZGS mappers and authors of each map. Each mapper employed several different techniques to best represent fault scarps indicative of previous surface-fault rupture or deformation over time. High-resolution topographic products derived from the lidar data proved to be the most useful tool when mapping; however, it was not exclusively used. In areas of urban development, pre-development stereo-paired images were used to identify and map fault traces. These photographs were particularly useful in identifying fault traces that have been obscured by development, among other uses. Satellite-based aerial imagery data (Utah Geospatial Reference Center, 2021) was useful for identifying color changes associated with bedrock faulting. Additional derivative lidar products such as slope-angle maps, slope-aspect maps, and topographic contours were used to discern fault scarps.

Fault activity classifications in the UGS *Utah Geologic Hazards Portal* and the USGS *Quaternary Fault and Fold Database of the United States* reflect the best available timing information for the most recent surface-rupturing earthquake on that fault trace, as well as lidar data, previous geologic mapping, and geomorphic relationships to determine these classifications. Each mapped fault trace was assigned a fault activity classification based on Lund and others (2020) and Western States Seismic Policy Council (WSSPC, 2018) guidelines. These definitions are as follows:

- Latest Pleistocene to Holocene – a fault whose movement in the past 15,000 years before present (ybp) has been large enough to break the ground surface.
- Late Quaternary – a fault whose movement in the past 130,000 ybp has been large enough to break the ground surface.
- Middle Quaternary – a fault whose movement in the past 750,000 ybp has been large enough to break the ground surface
- Quaternary – a fault whose movement in the past 2,600,000 ybp has been large enough to break the ground surface.

Special-Study Zone Delineation

We delineated surface-fault-rupture special-study zones along the Utah portions of the WHFZ, HFZ, and STFZ in accordance with Utah State Code 79-3-202(f) that define areas where additional investigation is warranted to evaluate the risk from surface faulting prior to residential, business, and infrastructure development. Together with the fault-trace mapping, these special-study zones are critical to the creation and implementation of municipal and county geologic-hazard ordinances associated with hazardous faults and understanding surface-rupturing hazard and associated risk.

We categorized Quaternary faults as “well defined,” “moderately defined,” or “buried or inferred” fault traces. We considered a fault well defined if its trace is clearly detectable by a trained geologist as a physical feature on the ground surface (Bryant and Hart, 2007). Additionally, lineaments that we were unable to conclusively prove were fault-related were mapped just as “lineaments.” For well-defined faults, the special-study-area zones extend 500 feet (152 m) on the downthrown side and 250 feet (76 m) on the upthrown side of each fault. For moderately defined and buried or inferred faults, the special study zones extend 1000 feet (305 m) on each side of the suspected trace of the fault. The special-study zone dimensions are based on the *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2020).

Several criteria were established for distinct circumstances pertaining to fault-related special-study zones. For traces of buried or inferred faults less than 1000 feet (305 m) long that lie between and on-trend with well-constrained faults, the well-constrained fault special-study-area zone was used (figure 6A). For buried or inferred faults greater than 1000 feet (305 m) long, the special study area includes 1000 feet (305 m) on both sides of the fault. For inferred faults at the end of a mapped fault trace that are longer than 1000 feet (305 m), we used an inferred fault special-study-zone area (figure 6B). Where two or more well-constrained faults are antithetic to, and within 250 feet of each other, the buffer zone created for the primary fault supersedes zones for any secondary faults. For example, a 500-foot (152 m) downthrown side special-study area on a main fault trace may extend beyond the 250-foot (76 m) upthrown side special study area associated with an antithetic fault, and therefore be used for the special-study zone. In areas where a buffer “window” exists (a space between the buffer zones of two sub-parallel fault traces), we include the window in the buffer zone if its width is less than the greater of the two surrounding buffers (figure 6C).

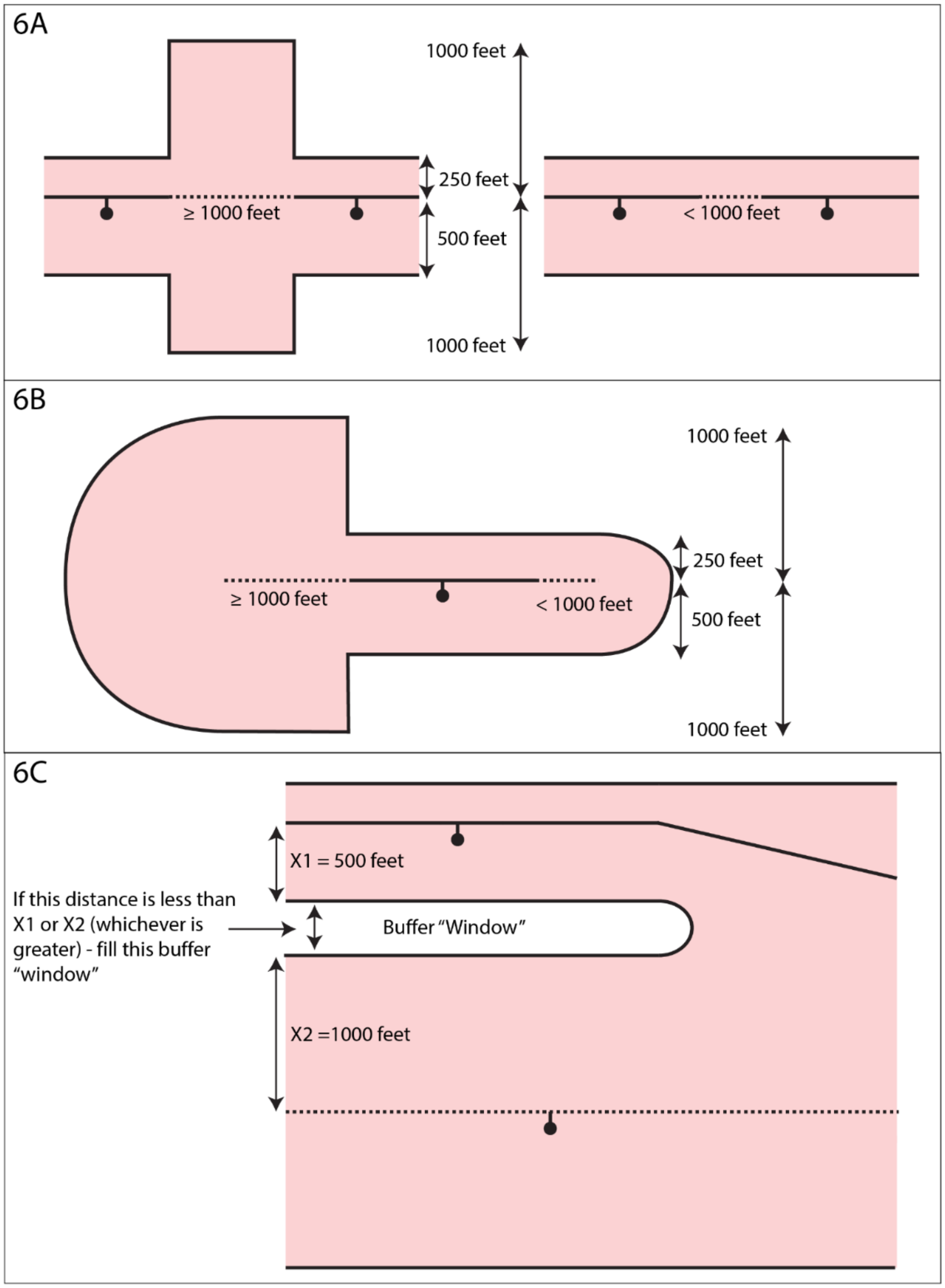

Figure 6 (left). *Examples of special circumstances used when creating surface-fault-rupture special-study zones.*

POTENTIAL PALEOSEISMIC INVESTIGATION SITES

We analyzed the HFZ, WFZ, STFZ, and other related faults for potential paleoseismic investigation sites as part of our fault-trace mapping. Sites were selected based on: (1) presence of a normal fault scarp, (2) scarp height that is reasonable for paleoseismic investigation (roughly 0.5–10 m), (3) scarp cutting young deposits (late Pleistocene to Holocene), and (4) mostly undisturbed. A list of 72 identified potential paleoseismic site locations are in table 1.

The UGS works to maintain a relationship with local geologic engineering firms and consultants who conduct trenching investigations for clients along hazardous faults. The UGS is often invited to visit consultant trenches for a few hours to observe and document faulting. Although not as useful as a full paleoseismic research investigation, these site visits still provide useful information in areas we will most likely never be able to conduct a full research-level investigation.

CONCLUSIONS

This report presents the motivation, process, and products funded by USGS External Grant Award Numbers G20AP0007 and G20AP00008 conducted by the UGS and the AZGS. We summarize new detailed mapping of the HFZ, WFZ, and STFZ in southwestern Utah and northwestern Arizona. Where permissible with available lidar coverage, we mapped some additional faults adjacent to and possibly structurally related to the HFZ. Our mapping methodology included the use of high-resolution airborne lidar-derived products, historical aerial photography, previous geologic mapping, and field investigations. The motivation for this work was timely due to the availability of the high-resolution lidar data, and the increasing population growth and development in these areas.

Special-study zones are defined in Utah based on the certainty of the fault trace mapping, and fault geometry. The special-study area dimensions are based on the *Guidelines for Evaluating Surface-Fault-Rupture Hazards in Utah* (Lund and others, 2020). These special-study zones are delineated in Utah in order to assist in land-use planning and regulation for local governments. Paleoseismic sites were identified along the WHFZ, HFZ, and STFZ in southwestern Utah and northwestern Arizona in order to foster future paleoseismic research in areas that are being rapidly developed or lacking good earthquake timing and recurrence information. We identified 72 potential sites with varying geologic conditions deemed potentially suitable for paleoseismic investigation (table 1). The 72 identified potential paleoseismic sites should not be considered a complete list of all sites on the mapped faults, as additional sites likely exist. We focused on identifying sites where the fault scarps are sparse given the nature of the fault and in areas where development and ongoing disturbance have obscured fault scarps. This dataset is designed to assist the UGS, AZGS, and other potential investigators in determining future sites for paleoseismic study.

The results of this work will be implemented in the form of a peer-reviewed UGS Report of Investigation (ROI) publication, a publication from the AZGS, and final publication of fault mapping in the UGS *Utah Geologic Hazards Portal* (https://geology.utah.gov/apps/hazards/) and the AZGS active fault theme on the *Natural Hazards in Arizona Viewer* (https://azgs.arizona.edu/quaternary-faults-natural-hazards-arizona-viewer). Once the final publication is complete, the UGS and AZGS will contact local governments to present them with the fault mapping and offer assistance in developing local ordinances based on special-study zones. These maps will serve as a critical tool to helping communities assess their earthquake risk and become more resilient to earthquake effects and geologic hazards.

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Table 1. *Potential paleoseismic sites along the Washington, Hurricane, and Sevier/Toroweap fault zones. Also includes potential sites for faults adjacent to the Hurricane fault zone: Volcano Mountain faults, North Hills faults, Cross Hollow Hills faults, Cedar Valley (west and north side) faults, Enoch graben faults, Red Hills fault, Parowan Valley faults, Paragonah fault, Parowan fault, Markagunt Plateau faults, and an unnamed fault near Leeds. The table identifies 72 sites and includes the potential site location as well as a cursory comment regarding good or poor qualities of the site for paleoseismic investigation.*

Site ID	Northing (UTM Zone 12N)	Easting (UTM Zone 12N)	FaultZone	Comments
STFZ-01	4079871 (UTM Zone 12S)	344505 (UTM Zone 12S)	Sevier/Toroweap fault zone	Site formed in fine-grained alluvial-fan deposits; W of distinct scarp in Moenkopi Formation bedrock; alluvium may be thin over bedrock. Located on the Kaibab-Paiute Indian Reservation.
STFZ-02	4073963 (UTM Zone 12S)	340935 (UTM Zone 12S)	Sevier/Toroweap fault zone	Fault zone exposed by arroyo development through fine-grained aeolian and older buff soils, and exposes bedrock Triassic Moenkopi; site reveals a dilated, 1 meter or less graben structure with soils offset approximately 0.5m to 1.0m below land surface; total fault zone is several meters wide or more; soils may be late Quaternary.
STFZ-03	4142897	367210	Sevier/Toroweap fault zone	Good scarp, lots of vegetation.
STFZ-04	4143521	367336	Sevier/Toroweap fault zone	Decent scarp, strong possibility of shallow bedrock in area.
STFZ-05	4143858	367539	Sevier/Toroweap fault zone	Good large scarp, strong possibility of shallow bedrock in area.
STFZ-06	4144155	367664	Sevier/Toroweap fault zone	Good scarp, potentially disturbed by unpaved road, strong possibility of shallow bedrock in area.
STFZ-07	4145146	368112	Sevier/Toroweap fault zone	Decent scarp, good access, close to town of Alton, strong possibility of shallow bedrock in area.
STFZ-08	4145672	368311	Sevier/Toroweap fault zone	Good scarp, good access, close to town of Alton.

STFZ-09	4149838	371963	Sevier/Toroweap fault zone	Interesting scarp, might be a decent trench site. Better access than scarp to S.
STFZ-10	4160310	376865	Sevier/Toroweap fault zone	Interesting scarp in mouth of Big Hollow Canyon. One of the only potential sites in the area.
STFZ-11	4196758	383255	Sevier/Toroweap fault zone	Older scarp on degraded fan, but (along with STFZ-12 & 13) only potential sites in area.
STFZ-12	4196878	383076	Sevier/Toroweap fault zone	Older scarp on degraded fan, but (along with STFZ-11 & 13) only potential sites in area.
STFZ-13	4197147	382784	Sevier/Toroweap fault zone	Older scarp on degraded fan, but (along with STFZ-11 & 12) only potential sites in area.
STFZ-14	4197727	383336	Sevier/Toroweap fault zone	Similar to STFZ-11, 12, & 13, but more potential for shallow bedrock.
SVF-01	4183196	378437	Sevier Valley (Hills near Panguitch) faults and folds	Very subtle scarp, but probably the youngest scarp in the Sevier Valley faults and folds. Combine with antithetic scarp to the east (SVF-02).
SVF-02	4183162	378667	Sevier Valley (Hills near Panguitch) faults and folds	See notes for SVF-01.
SVF-04	4189952	379522	Sevier Valley (Hills near Panguitch) faults and folds	Possibly one of the younger scarps in the Sevier Valley faults and folds system.
SVF-05	4191225	380273	Sevier Valley (Hills near Panguitch) faults and folds	Another target for multiple trench sites due to distributed zone of faulting.
SVF-03	4188736	378082	Sevier Valley (Hills near Panguitch) faults and folds	Target for multiple trench sites due to distributed zone of faulting.
SVF-07	4194300	381641	Sevier Valley (Hills near Panguitch) faults and folds	Intermediate scarp on good graben system cutting older fan. Combine with SVF-06 & 08.
SVF-08	4194432	381501	Sevier Valley (Hills near Panguitch) faults and folds	Westernmost scarp on good graben system cutting older fan. Combine with SVF-06 & 07 for full faulting history.

SVF-06	4194207	381767	Sevier Valley (Hills near Panguitch) faults and folds	Easternmost scarp on good graben system cutting older fan. Good scarp, combine with SVF-07 & 08 for full faulting history.
SVF-09	4196520	377005	Sevier Valley faults north of Panguitch	Site N of Anderson & Christenson (1989) trench. Younger looking subtle scarp, good target for potential trench if combined with other trenches to E & W.
SVF-10	4200081	378326	Sevier Valley faults north of Panguitch	Subtle scarp on younger fan. Decent site, combine with SVF-11 for full faulting history.
SVF-11	4200546	378766	Sevier Valley faults north of Panguitch	East-facing scarp, potentially degraded by fluvial channels at base of scarp. Combine with SVF-10 or -12 for full faulting history.
SVF-12	4200758	378369	Sevier Valley faults north of Panguitch	Subtle scarp on younger fan. Decent site, combine with SVF-11 for full faulting history.
WF-01	4102993	279368	Washington fault zone	Scarp on middle Pleistocene to Holocene alluvium/colluvium. Best site for paleoseismic trenching although bedrock may be encountered within a few meters.
WF-02	4113160	277226	Washington fault zone	Likely bedrock-cored scarp in partially disturbed, but rare undeveloped land in Washington City.
HFZ-01	4104202	295507	Hurricane fault zone	Only potential trench site on Utah part of Anderson Junction section. May be bedrock cored. Abundant talus may complicate excavation.
HFZ-02	4134072	298262	Hurricane fault zone	Ideal scarp for trenching formed by one of many faults antithetic to the Hurricane fault zone. May be used as a proxy for rupture timing on the main HFZ.
HFZ-03	4134669	297478	Hurricane fault zone	Scarp formed on fault antithetic to the Hurricane fault. Large boulders may be problematic. May be used as a proxy for rupture timing on the main HFZ.

HFZ-04	4146417	303161	Hurricane fault zone	"Water Tank site" of Lund and Others (2006); older, deeply dissected, and due to multiple strands, may not contain the full Quaternary faulting history.
HFZ-05	4159042	309677	Hurricane fault zone	"Coyote Gulch site" of Lund and others (2006). Relatively young scarp formed on late Pleistocene- to Holocene-age alluvium. Best potential site on HFZ in Utah.
HFZ-06	4161625	313041	Hurricane fault zone	"Bauer site" of Lund and others (2006). Complicated fault zone with many strands that would require multiple trenches. Some scarps may be bedrock cored.
HFZ-07	4164908	315072	Hurricane fault zone	"Middleton site" of Lund and others (2006). Complicated fault zone with many strands that would require multiple trenches. Some scarps may be bedrock cored.
EG-01	4183276	321702	Enoch Graben faults	Well-expressed scarp on fine-grained late Pleistocene to Holocene alluvial fan. One of many additional faults that compose the complex Enoch Graben.
EG-02	4183660	320016	Enoch Graben faults	2-m-high scarp formed on younger fine-grained alluvial-fan deposits. Great opportunity to study an actively creeping fault that has also had Holocene EQ rupture.
EG-03	4185836	320513	Enoch Graben faults	Similar to EG-2. Great opportunity to study an actively creeping fault that has also had Holocene earthquake rupture.
EG-04	4187632	322897	Enoch Graben faults	Well-expressed scarp on fine-grained late Pleistocene to Holocene alluvial fan. One of many additional faults that compose the complex Enoch Graben.
EG-05	4196870	326995	Enoch Graben faults	Moderately dissected 3-m-high scarp formed on late Pleistocene to Holocene alluvial fan. Rare scarp in central part of a mountain block.
CVW-01	4186584	312295	Cedar Valley (west side) faults	Moderately dissected 5-m-high scarp formed on fine-grained alluvium. Ideal target because the fault appears to be a single strand.

CVW-02	4183293	312007	Cedar Valley (west side) faults	Similar to CVW-01 site.
CVW-03	4170445	303531	Cedar Valley (west side) faults	Largest scarp (~3 m high) of three subparallel strands formed on late Pleistocene alluvium.
CVW-03	4160955	303540	Cedar Valley (west side) faults	Older, highly dissected scarp, but is best target for the southern end of the Cedar Valley (West Side) fault system.
CVN-01	4196704	323603	Cedar Valley (west side) faults	Well-preserved, 2-m-high scarp formed on level-2 (late Pleistocene to Holocene) alluvial fan. One of many potential sites in this multi-strand fault zone.
NH-02	4162467	312039	North Hills faults	An additional potential trench site on one of many poorly understood North Hills faults.
NH-01	4161646	311366	North Hills faults	One of the youngest-appearing scarps formed on older coarse basin-fill alluvium.
RHF-01	4188105	326856	Red Hills fault	3-m-high scarp formed on alluvial fan near mouth of unnamed drainage.
CHH-02	4171460	314119	Cross Hollow Hills faults	Ideal scarp for paleoseismic investigation located on one of the more prominent, throughgoing faults of this multi-strand fault system.
CHH-01	4170923	314410	Cross Hollow Hills faults	Ideal scarp for paleoseismic investigation located on one of the more prominent, throughgoing faults of this multi-strand fault system.
RHF-02	4188560	327243	Red Hills fault	Moderately dissected, 3- to 4-m-high scarp. Appears to have good access.
RHF-03	4198066	330688	Red Hills fault	Well-expressed scarp, but shallow bedrock may be encountered.
RHF-04	4199474	332250	Red Hills fault	Older, deeply incised scarp. Good access.
PVF-02	4199996	335717	Parowan Valley faults	Ideal trench site to develop new information on the Little Salt Lake fault.

PVF-01	4204151	343347	Parowan Valley faults	1-m-high scarp formed on Holocene fine-grained alluvium. Likely one of the youngest scarps in SW Utah.
PVF-03	4198351	341200	Parowan Valley faults	1-m-high scarp formed on Holocene fine-grained alluvium. Likely one of the youngest scarps in SW Utah.
PVF-04	4198310	340529	Parowan Valley faults	One of many low (<1 m high), young scarps in the Chimney Meadows.
PVF-05	4200245	341290	Parowan Valley faults	One of many low (<1 m high), young scarps in the Chimney Meadows.
PVF-06	4195603	331939	Parowan Valley faults	Young 1-m-high scarp. Same fault has displaced the Little Salt Lake playa a few 10s of m to the north. Some historical subsidence-related movement possible.
PVF-07	4207402	345461	Parowan Valley faults	1-m-high single-event scarp formed on younger fan. Good access.
PGF-02	4204958	350188	Paragonah fault	Older, but well-preserved 3-m-high scarp formed on middle to late Pleistocene alluvial fan.
PGF-01	4206406	350465	Paragonah fault	2- to 3-m-high scarp formed on older (middle to late Pleistocene) alluvial fan.
PGF-03	4193741	345073	Paragonah fault	Only late Pleistocene to Holocene scarp found on Paragonah fault. Other strands are present, but this scarp likely represents the MRE.
MP-01	4185492	333842	Markagunt Plateau faults	Only known scarp formed on unconsolidated deposits. Scarp faces uphill and is highly dissected.
PF-01	4192234	342761	Parowan fault	Well-preserved 2- to 3-m high scarp formed on late Pleistocene to Holocene alluvial fan.
PF-02	4191846	342643	Parowan fault	Alternative to PF-01, but scarp here is compound and consists of two closely spaced strands.

PF-03	4189999	341087	Parowan fault	Poorly preserved, moderately dissected scarp that may be bedrock cored.
PF-04	4189574	340291	Parowan fault	Short scarp adjacent to home. May possibly be bedrock cored. Additional strand to east.
PF-05	4189428	339829	Parowan fault	Potential trench site on prominent scarp at mount of Parowan Canyon. Adjacent to residential development and may be partially disturbed.
PF-05	4187196	332935	Parowan fault	Scarp formed on late Pleistocene to Holocene alluvial fan. Would have to trench an additional strand to the east for complete faulting history.
PF-06	4185403	330772	Parowan fault	Scarp formed on late Pleistocene to Holocene alluvial fan. Would have to trench additional nearby strands for complete faulting history.
LF-01	4125968	290287	Unnamed fault near Leeds	Well-developed scarp on coarse, bouldery alluvium. Trenching would be challenging due to large boulders and large (as much 10 m high) scarp height.

__Table 2.__ Geologic maps used to aid fault-trace mapping for each fault zone.

Map Name	Map Scale	Reference
Hurricane fault zone, Volcano Mountain faults, North Hills faults, Cross Hollow Hills faults		
Map Name	Map Scale	Reference
Geologic map of the St. George 30x60 quadrangle	100,000	Biek and others, 2009
Interim geologic map of the E¼ of the Cedar City 30x60 quadrangle	62,500	Knudsen and others, in press
Geologic map of the Divide quadrangle	24,000	Hayden, 2004
Geologic map of the Hurricane quadrangle	24,000	Biek, 2003a
Geologic map of the Pintura quadrangle	24,000	Hurlow and Biek, 2003
Geologic map of the Kolob Arch quadrangle	24,000	Biek, 2007
Geologic map of the Kanarraville quadrangle	24,000	Biek and Hayden, 2016
Interim geologic map of the Cedar City quadrangle	24,000	Knudsen, 2014b
Washington fault zone		
Map Name	Map Scale	Reference
Geologic map of the St. George 30x60 quadrangle	100,000	Biek and others, 2009
Geologic map of the northern part of the Fort Pearce section and the Washington Hollow section of the Washington fault zone	24,000	Knudsen, 2015
Geologic map of the Washington Dome quadrangle	24,000	Hayden, 2005
Geologic map of the Harrisburg Junction quadrangle	24,000	Biek, 2003b
Interim geologic map of the Washington quadrangle	24,000	Willis and Higgins, 1995
Sevier/Toroweap fault zone - Utah		
Map Name	Map Scale	Reference
Geologic map of the Kanab 30x60 quadrangle	100,000	Doelling, 2008
Geologic map of the Yellowjacket Canyon quadrangle	24,000	Hayden, 2013
Interim geologic map of the Mount Carmel quadrangle	24,000	Hayden, 2008
Coal and geology map, Orderville Canyon SW	24,000	Doelling and Graham, 1972
Coal and geology map, Orderville NE-SE	24,000	Doelling and Graham, 1972
Geologic map of the Alton quadrangle	24,000	Tilton, 2001
Geologic map of the George Mountain quadrangle	24,000	Biek, 2013
Geologic map of the Hatch quadrangle	24,000	Kurlich and Anderson, 1997
Preliminary geologic map of the Panguitch quadrangle	24,000	Moore and Straub, 1995
Geologic map of the Panguitch 30x60 quadrangle	100,000	Biek and others, 2015
Sevier/Toroweap Fault Zone - Arizona		
Map Name	Map Scale	Reference
Geologic map of the Fredonia 30x60 quadrangle	100,000	Billingsley and others, 2008
Geologic map of Pipe Spring National Monument and the western Kaibab Paiute Indian Reservation	24,000	Billingsley and others, 2004
Cedar Valley (North & West Side) faults and Enoch Graben faults		

Map Name	Map Scale	Reference
Interim geologic map of the E¼ of the Cedar City 30x60 quadrangle	62,500	Knudsen and others, in press
Interim geologic map of the Cedar City NW quadrangle	24,000	Knudsen and Biek, 2014
Interim geologic map of the Enoch quadrangle	24,000	Knudsen, 2014a
Geologic map of the Kanarraville quadrangle	24,000	Biek and Hayden, 2016
Red Hills fault, Parowan Valley faults, Paragonah fault, Parowan fault, and Markagunt Plateau faults		
Map Name	Map Scale	Reference
Geologic map of the Panguitch 30 x 60 quadrangle	62,500	Biek and others, 2015
Geologic map of the Parowan quadrangle	24,000	Maldonado and Moore, 1995
Geologic map of the Paragonah quadrangle	24,000	Maldonado and Williams, 1993a
Geologic map of the Parowan Gap quadrangle	24,000	Maldonado and Williams, 1993b